AD712 080

BOEING SCIENTIFIC RESEARCH LABORATORIES DOCUMENT D1-82-0993

BOEING

SCIENTIFIC RESEARCH LABORATORIES

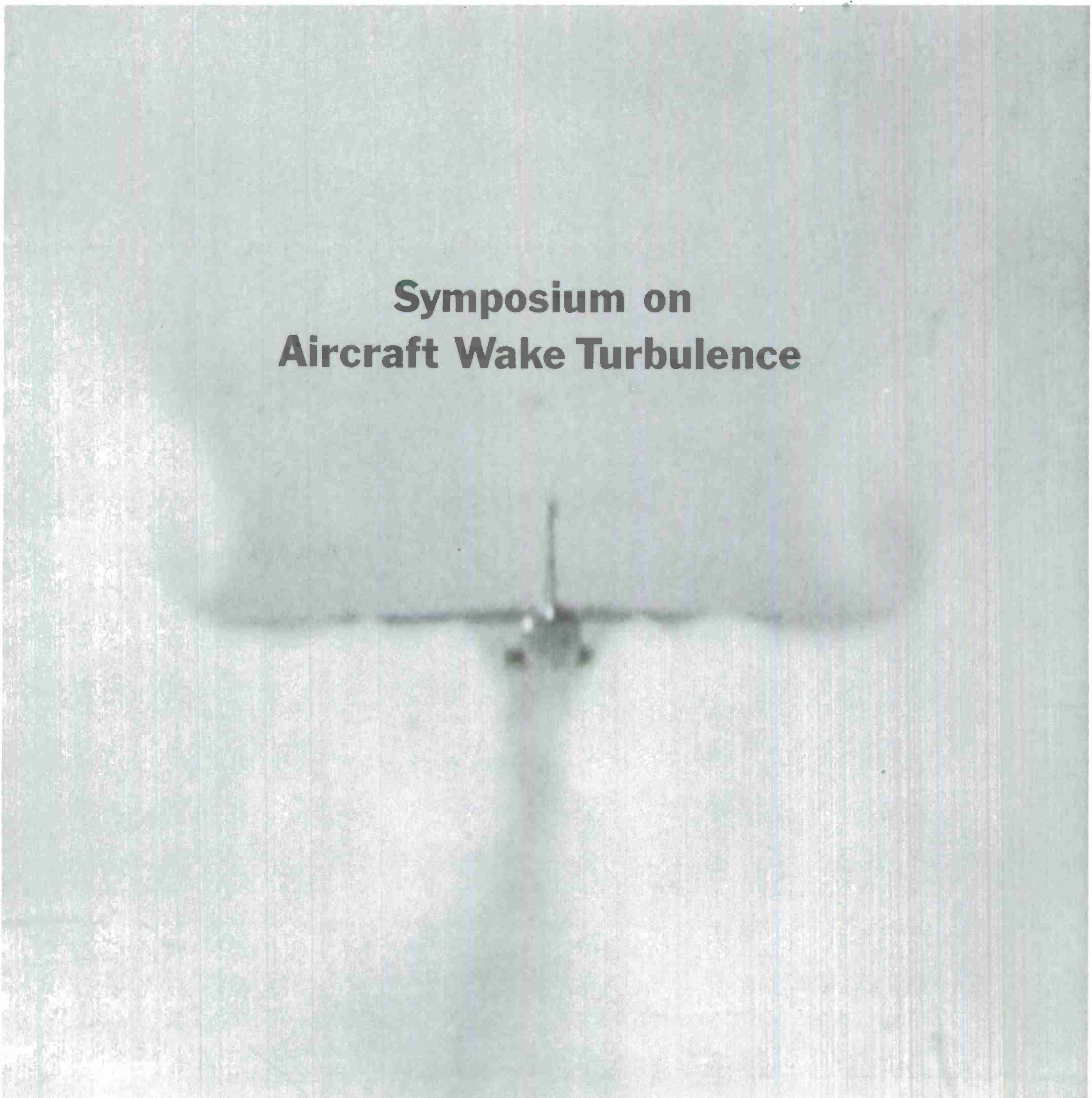
Symposium on Aircraft Wake Turbulence

FLIGHT SCIENCES LABORATORY SEPTEMBER 1970

DAILY SCHEDULE
AIRCRAFT WAKE TURBULENCE SYMPOSIUM

31 August Monday	1 September Tuesday	2 September Wednesday	3 September Thursday
REGISTRATION Washington Plaza Hotel 5-10:00 p.m.	SESSION I Fundamental Problems 10:15 a.m.	SESSION IV Wake Formation and Character 8:30 a.m.	SESSION VI Aircraft Response to Wake Turbulence 8:30 a.m.
RECEPTION 8-11:00 p.m.	SESSION II Experimental Methods 1:30 p.m.	SESSION V Stability and Decay of Trailing Vortices 1:30 p.m.	SESSION VII Control and Use of Trailing Vortices 1:00 p.m.
	SESSION III Flow Visualization Presentations and Results 7:30 p.m.		PANEL DISCUSSION 2:30 p.m.

Symposium on Aircraft Wake Turbulence



Air Force Office
of Scientific Research

Boeing Scientific
Research Laboratories

Seattle, Washington 1-3 September 1970

PROGRAM

AIRCRAFT WAKE TURBULENCE SYMPOSIUM

1-2-3 September 1970

Seattle, Washington

MONDAY, 31 AUGUST 1970

Registration, 5:00 - 10:00 p.m.   Washington Plaza Hotel

Reception, 8:00 - 11:00 p.m.

TUESDAY, 1 SEPTEMBER 1970

Registration, 8:00 a.m.

Welcoming Comments, 8:45 a.m.

Keynote Address, 9:00 a.m.

W. L. Shields, Jr. (Headquarters, United States Air Force)

Aircraft Wakes: A New Look at a Classical Problem

COFFEE BREAK

Session I. FUNDAMENTAL PROBLEMS, 10:15 a.m.

Chairman: P. R. Owen (Imperial College, London)

P. G. Saffman (California Institute of Technology):

The Velocity of Viscous Vortex Rings

L. Ting (New York University):

Studies in the Motion and Decay of Vortices

I. H. Tombach (Meteorology Research, Incorporated):

Transport of a Vortex Wake in a Stably Stratified Atmosphere

Session II. EXPERIMENTAL METHODS, 1:30 p.m.

Chairman: W. S. Luffsey (Federal Aviation Administration)

J. G. Olin and R. B. Kiland (Thermo-Systems, Incorporated):

Split-Film Anemometer Sensors for Three-Dimensional Velocity-Vector Measurement

R. L. Kiang (Stanford Research Institute):

Sub-Scale Modeling of Aircraft Trailing Vortices

COFFEE BREAK

C. C. Easterbrook and W. W. Joss (Cornell Aeronautical Laboratories):

The Utility of Doppler Radar in the Study of Aircraft Wing Tip Vortices

R. M. Huffaker (NASA, Marshall Space Flight Center); A. Jelalian, W. Keene, and C. Sonnenschein (Raytheon Company); and J. A. L. Thomson (Wayne State University):

Application of Laser Doppler Systems to Vortex Measurement and Detection

Session III. FLOW VISUALIZATION PRESENTATIONS AND RESULTS, 7:30 p.m.

Chairman: D. Coles (California Institute of Technology)

L. Garodz (Federal Aviation Administration):

Measurements of Boeing 747, Lockheed C5A and Other Aircraft Vortex Wake Characteristics by Tower Fly-By Technique

J. H. Olsen (Boeing Scientific Research Laboratories):

Towing Tank Observations of Wake Instabilities

J. E. Hackett and J. G. Theisen (Lockheed-Georgia Company):

Vortex Wake Development and Aircraft Dynamics

R. Child (The Boeing Company):

Recent Experiments on Wave Vortex Behavior of a Hovering Helicopter Rotor

R. E. Dunham, Jr. (NASA, Langley Research Center):

Photographs of Vortex Motion

V. R. Corsiglia, R. A. Jacobsen (NASA Ames Research Center); and N. A. Chigier (National Research Council):

An Experimental Investigation of Wing Trailing Vortices with Dissipation

T. Goodman (Oceanics, Incorporated):

Visualization of Wing Tip Vortices

R. W. Hale (Sage Action, Incorporated):

A New Approach for Visualizing Complex Airfoil Airflows

WEDNESDAY, 2 SEPTEMBER 1970

Session IV. WAKE FORMATION AND CHARACTER, 8:30 a.m.

Chairman: H. A. Liepmann (California Institute of Technology)

B. Caiger and D. G. Gould (National Aeronautical Establishment):

An Analysis of Flight Measurements in the Wake of a Jet Transport Aircraft

M. T. Landahl and S. E. Widnall (Massachusetts Institute of Technology):

Vortex Control

B. W. McCormick and R. Padakannaya (Pennsylvania State University):

The Effect of a Drooped Wing Tip on its Trailing Vortex System

COFFEE BREAK

P. L. Bisgood, R. L. Maltby and F. W. Dee (Royal Aircraft Establishment):

Some Work on the Behavior of Vortex Wakes at the Royal Aircraft Establishment

P. F. Jordan (Martin Marietta Corporation):

Span Loading and Formation of Wake

Session V. STABILITY AND DECAY OF TRAILING VORTICES, 1:30 p.m.

Chairman: S. C. Crow (Boeing Scientific Research Laboratories)

P. B. MacCready, Jr. (Meteorology Research, Incorporated):

An Assessment of Dominant Mechanisms in Vortex-Wake Decay

S. E. Widnall, D. Bliss, and A. Zalay (Massachusetts Institute of Technology):

Theoretical and Experimental Study of the Stability of a Vortex Pair

D. W. Moore (Imperial College) and P. G. Saffman (California Institute of Technology):

Structure of a Line Vortex in an Imposed Strain

COFFEE BREAK

P. C. Parks (NASA, Langley Research Center and University of Warwick):

A New Look at the Dynamics of Vortices with Finite Cores

C. duP. Donaldson (Aeronautical Research Associates of Princeton, Incorporated):

Decay of an Isolated Turbulent Vortex

J. N. Nielsen and R. G. Schwind (Nielsen Engineering and Research):

Decay of a Vortex Pair Behind an Aircraft

THURSDAY, 3 SEPTEMBER 1970

Session VI. AIRCRAFT RESPONSE TO WAKE TURBULENCE, 8:30 a.m.

Chairman: J. H. Bollard (University of Washington)

P. M. Condit and P. W. Tracy (The Boeing Company):

Results of The Boeing Company Wake Turbulence Test Program

J. C. Houbolt (Aeronautical Research Associates of Princeton, Incorporated):

Aircraft Response to Turbulence Including Wakes

W. P. Jones and B. M. Rao (Texas A & M University):

Airloads and Moments on an Aircraft Flying Over a Pair of Inclined Trailing Vortices

COFFEE BREAK

W. H. Andrews (NASA, Flight Research Center):

Flight Evaluation of the Wing Vortex Wake Generated by Large Jet Transports

R. P. Johannes (Air Force Flight Dynamics Laboratory):

Aircraft Wake Turbulence Controllability Experiment

Session VII. CONTROL AND USE OF TRAILING VORTICES, 1:00 p.m.

Chairman: A. Goldburg (Boeing Scientific Research Laboratories)

J. Menkes (University of Colorado) and F. H. Abernathy (Harvard University):

An Estimate of the Power Required to Eliminate Trailing Vortices by Suction

P. O. Baronti and S. Elzweig (Advanced Technology Laboratories):

Fog Formation and its Dispersal by Trailing Vortices

COFFEE BREAK

Panel Discussion. DIRECTIONS FOR FUTURE RESEARCH, 2:30 p.m.

Chairman: A. Goldburg (Boeing Scientific Research Laboratories)

S. C. Crow (Boeing Scientific Research Laboratories)
J. N. Garrison (Air Force Flight Dynamics Laboratory
P. R. Owen (Imperial College)
W. S. Luffsey (Federal Aviation Administration)
D. Coles (California Institute of Technology)
H. A. Liepmann (California Institute of Technology)
J. H. Bollard (University of Washington)

ABSTRACTS OF PAPERS

The abstracts are listed according to their order in the program. The majority of the abstracts have been retyped at the Boeing Scientific Research Laboratories.

KEYNOTE ADDRESS

BY

W. L. Shields
Colonel, USAF
Headquarters, United States Air Force
Washington, D. C. 20033

Aircraft Wakes: A New Look at a Classical Problem

W. L. Shields
Colonel, USAF
Headquarters, United States Air Force
Washington, D. C. 20033

Aeronautical research has experienced a sort of renaissance, after a period of being overshadowed by space research. Aerodynamic vortices provide an excellent example of an aerodynamic problem in which interest has been revived, not only because of continuing scientific importance, but because of important operational considerations as well.

Aerodynamic vortices, like some other classical problems of fluid mechanics, have displayed in their short history a pattern of unfolding complexity. The seemingly simple early visualization of the phenomenon has given way to a complex, three-dimensional concept. The unfolding complexity of the problem provides many potential areas of basic and applied research.

The potential research areas contained within the aircraft wake vortex problem seem to fall naturally into a few major categories: vortex formation, vortex decay and breakup, interaction of vortices with the environment, operational problems, and experimental techniques. The symposium program includes excellent papers in each of these categories.

This symposium promises to serve several purposes. It can provide a focus for renewed interest in aeronautical research in government, industry and the universities. It can identify opportunities to apply basic research to pressing real-world problems. Finally, it can develop and illuminate many challenging research topics in basic fluid mechanics.

SESSION I

Fundamental Problems

The Velocity of Viscous Vortex Rings[†]

P. G. Saffman
California Institute of Technology
Pasadena, California 91109

The motion of vortex rings of small cross section is considered. A formula is derived for the velocity of a ring in an ideal fluid with an arbitrary distribution of vorticity in the core. The effects of viscosity are then examined. A definition of the velocity of an unsteady diffusing ring is given and it is shown that the method used to calculate the ring speed in an ideal fluid can be extended to give the velocity of a vortex ring subject to viscous diffusion.

[†] To appear: Studies in Applied Mathematics, December 1970.

Studies in the Motion and Decay of Vortices*

L. Ting
Department of Mathematics, New York University
Bronx, New York

Solutions of Navier-Stokes equations are constructed as an asymptotic expansion in terms of a small parameter related to the Reynolds number of the vortex. A general scheme is presented for the matching of the inner viscous core of the vortex to the outer inviscid solution. The leading term for the inner viscous core is given by a similar solution and that for the outer solution is the classical inviscid solution. The requirement that there is no singularity in the flow field defines the velocity of the vortex line. Based upon this general scheme the results for vortices in two dimensional streams, circular vortex rings in axially symmetric streams and for a curved vortex line in a general three-dimensional flow field are presented. Numerical examples are presented to show the differences in the motion of the vortex line given by the present analysis with that from the inviscid theory with a finite core of uniform vorticity. The application of present analysis for vortices with a given initial velocity profile different from that of a similar solution is described. When the initial velocity of the vortex is different from that given by the present asymptotic analysis, either due to a sudden release of the vortex or due to a sudden change in the outer flow field, the necessary modifications to the analysis is presented and the solution for the subsequent motion of the vortex line is presented.

---

*This research supported by AFOSR Grant 67-1062C

Transport of a Vortex Wake In a Stably Stratified Atmosphere

Ivar H. Tombach
Meteorology Research, Inc.
Altadena, California 91001

Atmospheric stratification affects the downward motion of an aircraft vortex wake and can influence the persistence and stability of the vortex pair configuration. Observations of actual wakes have shown significant variation in the distance to which they descend and in their lifetime under different degrees of atmospheric stability. This behavior has been modeled analytically as a pair of infinite vortices in an inviscid, compressible, stably stratified atmosphere. It has been found that the motion of such a vortex system is governed by a parameter

$$Q = \text{const.} \frac{\Gamma_o}{sR_o^2} \left[- \frac{1}{\rho_o} \frac{d\rho^*}{dz} \right]^{-1/2} ,$$

where the initial configuration consists of a pair of vortices of circulation Γ_o, spaced $2R_o$ apart, with a density ρ_o and no buoyancy. The term $d\rho^*/dz$ is the density gradient of the atmosphere relative to the adiabatic density gradient and is required to be negative (stable atmosphere). Entrainment of the surrounding atmosphere is characterized by s, which is related to the difference between the mean density of the fluid being entrained and that within the vortex system.

The parameter Q has a critical value, $Q_{crit.} = \pi/2$ which divides the transport of a vortex wake into two patterns, depending on whether Q is less than or greater than $Q_{crit.}$. If $Q<Q_{crit.}$, the circulation

decreases more rapidly than the momentum and the vortices separate as they descend to an equilibrium level. The behavior is similar to that of a vortex pair in ground effect, except that the velocity of divergence grows without bound.

If $Q>Q_{crit.}$, the momentum of the vortices decreases more rapidly than the circulation and, after an initial period of slow divergence, the vortices attempt to converge as they descend to an equilibrium level. The critical case, $Q=Q_{crit.}$, results when the momentum and circulation decay to zero simultaneously as the vortices descend, at which point they are spaced $1.33 \times 2R_o$ apart. In all cases, the descent to the equilibrium level takes place in a well-defined characteristic time which depends solely on the density gradient, $-d\rho^*/dz$.

For most modern aircraft (ranging from the DC-3 to the Boeing 707) the ratio Γ_o/R_o^2 is of the order of 1.2 sec^{-1}; but for the Concorde, it is about 4.0 sec^{-1}. Thus, under identical atmospheric conditions (and ignoring any influence of aircraft-caused turbulence on s), the wake of the Concorde would be expected to behave differently than the wakes of the DC-3 or Boeing 747.

Since one of the methods by which the aircraft wake decays is by breakup of the parallel configuration because of vortex interactions, the effect of atmospheric stability on the vortex spacing can have a strong effect on the stability of the vortex pair. In particular, one would expect the case in which the vortices converge as they descend ($Q>Q_{crit.}$) to be particularly unstable and the lifetime of the organized wake to be quite short.

SESSION II

Experimental Methods

Split-Film Anemometer Sensors for Three-Dimensional Velocity-Vector Measurement

J. G. Olin and R. B. Kiland
Thermo-Systems, Inc.
St. Paul, Minnesota 55113

A probe for the fast-response measurement of the total air velocity vector is described. In the past, velocity-vector measurement has been achieved with a probe consisting of three, orthogonal, hot-film sensors. However, this measurement requires an a priori knowledge of the octant of the velocity vector. The present probe is identical but uses split-film sensors to provide automatic octant indication. Each hot-film sensor consists of a 6-mil diameter, 80-mil long cylindrical quartz rod coated with a 1000 Å platinum film. The film of this new sensor is axially segmented, or split, with two splits 180° apart. Each split film is electrically heated to the same constant temperature by a separate electronic constant-temperature anemometer control system. The non-uniformity of heat flux around the sensor is detected by comparing the individual heat flux to each split film. For Reynolds numbers less than approximately 5×10^4, the heat flux to the upstream split film is greater than the downstream. This is used to detect the sense of the velocity component normal to the sensor. Such information from all three orthogonal sensors yields the octant of the air velocity vector. The sum of the heat fluxes to the two split-films of a sensor is invariant with azimuthal angle. This permits the use of standard techniques to measure the magnitude and direction of the velocity vector within the detected octant.

Experimental data and empirical correlations are presented for the variation of heat flux with velocity magnitude and two directional angles - the normal and azimuthal angles to the sensor. The heat-flux ratio of the downstream to the upstream split film has a simple quadratic dependence on a imuthal angle. The sum of the two heat fluxes to a sensor is correlated in the typical fashion with an effective cooling velocity. The paper describes alternative data-reduction procedures.

Sub-scale Modeling of Aircraft Trailing Vortices

Robert L. Kiang
Stanford Research Institute
Menlo Park, California 94025

Most experimental studies of trailing vortices have been conducted with one of the following three methods. 1. Wind-tunnel study; suitable for the study of vortex formation, but not the long-time decay process. 2. Intercepting vortices shed by one airplane with another airplane. This would have been the most realistic approach, but unfortunately, the difficulty in coordinating the two traveling airplanes plus the various unknown effects of the atmosphere have so far precluded any consistent and useful data. 3. Record the vortices shed by a low flying airplane with ground-based instruments. This kind of study inevitably includes the ground effect on top of all the unpredictable atmospheric effects. The data obtained, though useful to the air-traffic control near the runways, are nevertheless hard to analyze and separate the various mechanisms responsible for the vortex decay.

The present paper describes a pilot study of trailing vortices using a sub-scale model in a more controllable laboratory environment. The essential feature of this laboratory facility is to have a vortex-generating wing moving along a pair of elevated rails so that the vortices shed by the wing remain relatively fixed with respect to ground-based instrumentation and can be observed and measured throughout their entire life-span. The vortices are rendered visible by two methods. One by smoke traces and

the other by drifting soap bubbles. A 16-mm movie camera is used to record the visible vortices. The smoke-traced vortices give better qualitative pictures but the soap-bubble pictures are more suitable for quantitative studies. Hot-wire anemometer probes are also used to study the turbulence nature of the vortices. Ease of operation, repeatability, and versatility are some of the obvious advantages of this experimental setup.

Geometrically similar wings of different sizes running at various speeds and angles of attack are tested. The vortices generated by these model wings all contain high levels of turbulence. They generally last for a few seconds. A scaling study is also described based on existing theories which predict the decay rate of a turbulent line-vortex. None of the theories examined is capable of correlating the results of the sub-scale experiments (chord Reynolds number of the order of 10^5) and those of full-scale airplanes (chord Reynolds number ranging from 10^6 to 10^8). This indicates that a satisfactory theory of turbulent vortex decay is still lacking.

The Utility of Doppler Radar in the Study of Aircraft Wing-Tip Vortices

Calvin C. Easterbrook and William W. Joss
Cornell Aeronautical Laboratory, Inc.
Buffalo, New York 14221

A measurement technique is investigated whereby the motions of radar scatterers distributed in an aircraft wake are sampled by a special purpose pulsed-doppler radar. It is shown that the power spectrum obtained in this manner is a measure of the velocity distribution of scatterers in the direction of the radar beam weighted by the spatial distribution of the scattering elements within the radar sensitive volume. If the scattering elements have low mass and high drag-to-weight ratio, they will follow very closely the motion of the air in which they are imbedded. Therefore, measurement of scatterer motion under these circumstances reflects the air motion to a good approximation. Two similar but unique methods were tried in attempts to verify the utility of the doppler radar technique. The first approach involved dispensing radar reflecting chaff from the wing-tip of an aircraft in flight, and subsequently recording the doppler-spectrum of the radar return from the chaff packet as viewed by the radar looking normal to the flight path. Doppler-spectra obtained from two test flights with a Piper Aztec aircraft were in good agreement with azimuthal velocities expected from this small aircraft. Furthermore, the measured decay rates indicate that the chaff elements remain in the vortex core area for at least one minute, even with the relatively weak radial inflow likely to exist.

The second method investigated required the aircraft to fly through an existing, uniform distribution of scatterers. Measurements were made behind aircraft making instrument approaches to an airport during periods of snowfall. Again some encouraging results were obtained, although certain operational difficulties were encountered that were related to the use of available, unmodified radar equipment.

Application of Laser Doppler Systems to Vortex Measurement and Detection

Robert M. Huffaker
NASA/Marshall Space Flight Center
Moffett Field, California 94035

A. Jelalian, W. Keene, and C. Sonnenschein
Raytheon Company
Sudbury, Massachusetts 01776

and

J. A. L. Thomson
Wayne State University
Detroit, Michigan 48202

A laser Doppler system for the measurement of atmospheric wind velocity and turbulence has been developed. This system utilizes the Doppler frequency shift undergone by a beam of radiation when scattered by particles suspended in the flows. From the measurement of this difference frequency between the scattered and the reference laser light and knowledge of the geometry of the system, the velocity is directly determined. A three dimensional system has been developed for wind tunnel and jet type flow studies. Using this system, measurements of velocity have been made in wind tunnels and in jet flows with velocities in excess of Mach 2 and compared with theory and hot wire instrumentation. The agreement was good.

Using the concept proven in wind tunnel aerodynamic applications, the feasibility of extending the technique to the measurement of atmospheric wind velocity and turbulence was demonstrated. A one-dimensional research unit has been developed. Using this one-dimensional laser Doppler system, measurements of atmospheric wind velocity

have been made and good comparisons with simultaneous cup-type anemometer measurements has been demonstrated. These comparisons in mean wind velocity will be presented. Comparisons with cup and hot wire anemometer data with the laser Doppler system for measurement of the time history of the wind velocity and the statistical properties of the wind velocity fluctuation will also be presented. Comparisons for different types of wind conditions will be presented.

This Doppler system has also been applied to the problem of detecting the presence of an aircraft trailing vortex. Results of the test program will be presented. The results showed that when the vortex was visually sighted and known to be in the sensitive scattering volume of the laser Doppler system, the velocity distribution of the vortex was measured. Consideration for a three-dimensional research system for monitoring the presence and velocity structure of aircraft trailing vortices will be given. Operational consideration for an airport warning system will also be presented.

SESSION III

Flow Visualization Presentations and Results

Measurements of Boeing 747, Lockheed C5A and Other Aircraft Vortex Wake Characteristics by Tower Fly-By Technique

Leo J. Garodz
Federal Aviation Administration
National Aviation Facilities Experimental Center
Atlantic City, New Jersey 08405

Flight tests have been conducted by the FAA at both the ESSA/AEC facility, Idaho Falls, Idaho, and NAFEC, Atlantic City, New Jersey, during the period 18 February 1970 through 3 August 1970 to gather quantitative data on aircraft vortex wake characteristics using the tower fly-by technique. Aircraft tested included the Boeing 747, 707-300 and 727-100, the Douglas DC-8-63F, DC-8-33 and DC-9-10, the Lockheed C5A, the Convair 880, and the Learjet 24. A 200-foot and a 100-foot tower was used at the ESSA and NAFEC test sites, respectively. Vortex flow visualization for vortex characteristics and movement was provided by smoke grenades mounted on the towers and by injecting CORVIS-type oil into the outboard jet engine exhausts of certain aircraft with wing mounted engines.

Vortex flow velocities were obtained using hot-film/hot-wire sensors.

Measured tangential velocities were approximately double those velocities predicted by certain theory (which assumes an elliptical lift distribution).

Distinct vortex characteristics peculiar to certain model aircraft and configurations per aircraft model were noted: (1) T - tail aircraft with engines mounted on the fuselage, i.e., the B-727 and DC-9 were observed to produce much higher tangential velocities on the order of 175 - 200 feet/second than aircraft with engines mounted on the wing,

e.g., the B-707, B-747 which were on the order of 130 feet/second.
(2) For "clean" configuration and small flap deflections, the vortex systems of all the aircraft were observed to be of a tubular form, relatively small in diameter, very clearly structured and very persistent. For greater flap deflections, vortices of tubular form were much less evident. With the exception of the B-727 and DC-9, when maximum flap deflections were employed, this characteristic was not observed, the vortex appearing much larger in diameter, i.e., field of influence.
(3) From visual flow observations of the tubular-type vortex system when highest vortex tangential velocities were recorded, the core radius as outlined by the tower smoke appeared to be small; approximately 5 - 6 feet for the larger B-747 and C5A aircraft to 1-foot for the B-727 and DC-9 type aircraft.

Particular attention was given vortex axial flow phenomena by observing and photographically recording entrainment of the colored smoke. When tubular-type vortex systems passed the tower, smoke was clearly entrained and spontaneously moved within the vortex system along its axis in both directions, i.e., up and down flight path. A vortex has a low pressure area within its cylindrical wall analagous to a tornado or water spout. Once the wall is penetrated, as by the instrumented tower upon vortex passage, there is an immediate injection of relatively higher pressure ambient air which carries the colored smoke in both axial directions in the attempted pressure equalization process.

It is possible that the tower technique may cause premature vortex instability onset when the vortex tube passes through the tower with subsequent valid data acquisition on that particular vortex questionable.

Towing Tank Observations of Wake Instabilities

J. H. Olsen
Boeing Scientific Research Laboratories
Seattle, Washington 98124

Flow visualization studies with an electrochemically activated dye technique were performed in a towing tank. Test Reynolds numbers (approximately 2×10^4) were far lower than in flight conditions, but the results may suggest useful theoretical of flight test investigations. Starting and stopping effects were shown to be confined to the neighborhood of the tank ends.

The vortex core contains an axial jet in the direction of the wing motion. An instability which enlarges the core without destroying the motions far from the core was observed and found to correlate with theoretical results of Bergman[1] on the instability of a vortex containing a jet.

Possibilities for using the flow visualization method for investigating ground effect and various vortex destruction techniques are discussed.

[1] Bergman, K. H., 1969: On the Dynamic Stability of Convective Atmospheric Vortices. Ph.D. Thesis, Department of Atmospheric Sciences, University of Washington.

Vortex Wake Development and Aircraft Dynamics

J. E. Hackett and J. G. Theisen
Lockheed-Georgia Company
Marietta, Georgia 30060

The dynamics of vortex wakes are depicted in the forms of smoke flow visualization and computer graphics displays. Smoke, injected into the core of the trailing vortex behind a 13-foot-span C-130 wing-tunnel model, demonstrated remarkable coherence until the diffuser section of the wind tunnel was reached. Here, the adverse pressure gradient caused premature vortex breakdown, but at a position consistent with an approximate analytical study. In a theoretical study, the 'wavy' distortion mode of a pair of line vortices with cores was simulated; computer graphic displays shown are reminiscent of contrails seen at altitude. V/STOL aircraft produce high-lift wakes which have unusual geometry due to local lift concentration, such as part-span flaps, lifting jets, etc. Smoke flow visualization is shown for the formation of vortices in a round jet, typical of direct-lift VTOL. The motions of a following aircraft obliquely entering the vortex trail of a leading aircraft have been calculated using equations of motion with six degrees of freedom. The calculated solution shows similarity to motions observed in flight tests. A blend of theoretical and experimental procedures has been applied at Lockheed towards the determination of vortex decay/distortion/dissipation

processes. Certain aircraft size parameters appear in the theoretical formulation, providing some trends concerning model scaling effects. Greater use of adequately sized wind tunnel test facilities is suggested for the conceptual testing of devices for inducing tip vortex attenuation. Considerable cost savings are possible relative to flight testing techniques.

Recent Experiments on Wake Vortex Behavior of a Hovering Helicopter Rotor

Richard F. Child
The Boeing Company
Philadelphia, Pennsylvania 19142

Noise has become a major consideration in the design of aircraft to the extent that performance will be compromised if necessary to avoid either community annoyance or aircraft detection problems. Consequently, aerodynamicists and acousticians are confronted with the problem of identifying the origins of aircraft noise and developing a means of eliminating or significantly reducing noise without restricting performance.

Rotary wing aircraft have a type of noise signature associated with the rotor which has been labelled rotor slap or bang. This is an impulsive noise long associated with blade/vortex interactions. Recent investigations have disclosed that a direct interaction between blade and vortex is not required to generate bang. A blade/vortex clearance of approximately one chord length is sufficient to produce the noise. Therefore, the behavior of the trailed vortex system is of intense interest to rotary wing aerodynamicists.

Experimental studies of trailed rotor vortex behavior conducted by the Boeing Vertol Division are described in this presentation. Smoke was injected into the tip vortex of a rotor blade and high-speed cameras recorded the motion of the vortex relative to the rotating blade system and stationary ground or translating aircraft system. The results show

that for forward flight the vortex system trajectory is reasonably well calculated by existing theory. For the hovering rotor, however, the vortex trajectory is not as predicted, and a large number of instabilities appear which could significantly alter the blade/vortex interaction behavior.

Photographs of Vortex Motion

R. Earl Dunham, Jr.
NASA Langley Research Center
Hampton, Virginia 23365

Flow visualization of full scale aircraft trailing vortices has been used to obtain a qualitative determination of vortex characteristics. Two techniques were used to illuminate the vortex, (1) smoke was injected at each wing tip of the test aircraft or (2) the test aircraft was flown past a tower which supported smoke bombs. For all film sequences shown the vortices were generated by a C-47 aircraft. Selected films taken using the tower technique clearly illustrate the longitudinal flow within the core and the induced flow field outside the core; whereas photographs of wing-tip injected smoke are used to show the movement of vortices under the influence of winds and close proximity to the ground.

Tests were also conducted to determine the effect of slicing the vortex normal to its axis and stagnating the longitudinal flow, thereby inducing an artificial breakdown. These tests showed that the vortex was destroyed at its point of contact with the obstacle and this disturbance propagated upstream and downstream. In addition, the film illustrates the three natural modes of vortex decay-diffusion, sinusoidal instability, and bursting.

An Experimental Investigation of Wing Trailing Vortices with Dissipation

Victor R. Corsiglia

Robert A. Jacobsen

NASA Ames Research Center
Moffett Field, California 94035

Norman A. Chigier
National Research Council Associate

Trailing vortices persist over long distances and present a hazard to following aircraft. The objective of the present investigation was to determine if it was possible to increase the rate of dissipation of these vortices and, in particular, to reduce the magnitude of the tangential velocities.

An experimental study was made on a rectangular wing in the NASA-Ames 7- by 10-Foot Wind Tunnel. Flow visualization studies were made using a tuft grid and smoke. Preliminary studies showed that the introduction of a bluff body into the trailing vortex downstream of the wing resulted in dissipation of the vortex. Further studies showed that a small vertical panel mounted on the wing upper surface near the wing tip also caused dissipation of the vortex . This vertical panel (termed a vortex dissipator in the following discussion) had a height of 12% of the wing chord and a width of 4% of the wing semispan.

Both the smoke and tuft grid visualization studies indicated that the dissipator caused a significant reduction in the maximum tangential velocities near the vortex. Additional studies using a hot-wire anemometer showed significant reductions in the magnitude of the tangential velocities

and increases in the turbulence level and cross-sectional dimensions of the dissipated vortex.

Further studies of the flow in the trailing vortices both with and without the dissipator are continuing. Also, a flight test is planned to investigate the effectiveness of the dissipator in flight.

Visualization of Wing Tip Vortices

Theodore R. Goodman
Oceanics, Inc.
Plainview, New York 11803

Investigations carried out in a water tunnel are currently underway to determine the destabilizing effect of sound waves on a vortex pair. In conjunction with this work the stability of a vortex pair in ground effect and in the presence of a jet exhaust are being studied analytically. None of this work is presently complete and so the entire presentation consists of a 10-minute motion picture in color and sound illustrating the use of a bubble technique for rendering free vortices visible in a water tunnel. This work had been performed earlier in conjunction with studies of the wing-tail interference of aircraft.

A New Approach for Visualizing Complex Airfoil Airflows*

R. W. Hale
Sage Action, Inc.
Ithaca, New York 14850

A new technique for airflow visualization is discussed in which small, neutrally-buoyant bubbles are used as flow tracers. These bubbles are filled with helium gas and range in size from 1/16" to 1/4" in diameter depending upon the desired application. They are rapidly generated by a compact "head" in a continuous manner at rates as high as 250 bubbles per second. One head design is described that is capable of implanting bubbles in airflows at speeds up to 200 fps or more. Since the bubbles can be viewed or photographed individually, they are especially well-suited to mapping turbulent wakes and separated flow regions. To illustrate the technique, recent pictures taken of streamline patterns about a two-dimensional, Karman-Trefftz airfoil are presented.

*This work was supported by the Aeronautics Branch of the Office of Naval Research under Contract N00014-68-C-0434.

SESSION IV

Wake Formation and Character

An Analysis of Flight Measurements in the Wake of A Jet Transport Aircraft

B. Caiger and D. G. Gould
National Research Council
Ottawa, Ontario, Canada

Measurements have been made of the vortex wake behind an F.A.A. Convair 880 aircraft using an instrumented T-33 aircraft of the National Aeronautical Establishment, Canada. The Convair 880 was flown at an indicated airspeed of 220 knots at 30,000 feet, the T-33 following at approximately the same speed and making slow lateral traverses of the wake at separation distances varying between ½ and 3 nautical miles.

From high frequency response vanes mounted on a nose-boom, it was found that peak transverse velocities of 130 feet per second were present even at the maximum separation distance, where estimates would have predicted only 32 feet per second. A detailed analysis was therefore made of the time histories of the transverse velocity vectors during several of the traverses. These suggested that the large velocity peaks were associated with small intense vortices embedded in the flow pattern of the two main wing-tip vortices.

A theoretical vortex wake model incorporating one such small vortex on each side was derived and traverses through this model compared with the flight measurements, reasonable agreement being obtained. It would appear that the small vortices have a core diameter of the order of 1.3 feet which is roughly independent of the separation distances covered. Their strengths are roughly consistent with the lift induced on the body and it is suggested that they may be shed from the wing-body junction.

The lack of growth in core size may be due to high axial velocities in the core associated with large total head losses at the point where they are generated.

The presence of the small vortices made accurate assessment of the strength and dissipation of the main vortices difficult. However, a few traverses in which small vortices were not intercepted show the classical velocity distribution associated with a single pair of trailing vortices and confirm that the peak velocities are in rough agreement with past estimates, although they do not change significantly with separation distance over the range tested.

Vortex Control

M. T. Landahl

and

S. E. Widnall

Massachusetts Institute of Technology
Cambridge, Massachusetts 02138

The fluid dynamical aspects of the control of free vortices emanating from wing, fuselage, or other parts of a flight vehicle are reviewed. A successful design calls for control of vortex strength, position and stability. In addition, it may in some situations be desirable to control vortex core size.

The strength of the vortex is determined from the boundary layer separation, which in turn is strongly influenced by the presence of the vortices themselves. It is therefore a very difficult analytical problem to predict the vortex strength, and this can be solved only in simple cases with sharp edges on the lifting surface, for which a generalized Kutta condition can be applied to ensure a vortex configuration producing stagnation points at such edges. Vortex generators operate on the principle of introducing a sharp edge at the position where one desires the vortex to originate. In view of the very complicated vortex-boundary layer problem involved, the problem of the design of a vortex generator must be approached through wind tunnel experimentation, but simple fluid dynamical considerations can provide useful guidelines.

The location of a vortex can be influenced by interference with other lifting surfaces, or the fuselage, or by the presence of other vortices. Potential flow theory is generally adequate for the determination of the vortex location, but difficult nonlinear problems due to the complicated nonlinear interaction usually arise. Some possible numerical approaches are discussed.

The attainable vortex strength is often limited by the phenomenon known as vortex bursting. The different explanations proposed for bursting are reviewed. These point to the possibility of preventing bursting by limiting the axial pressure gradients in the core. A favorable pressure gradient may be achieved through interference with other vortices and lifting surfaces. Vortex core size is influenced by the details of the roll-up process and by any stretching or compressing of the vortex.

Some examples of vortex control are given. In particular, the scheme employed for the Swedish J 37 "Viggen" to delay vortex bursting is described.

The Effect of a Drooped Wing Tip on Its Trailing Vortex System

B. W. McCormick

R. Padakannaya

The Pennsylvania State University
University Park, Pennsylvania 16802

The effect of wing tip droop on the structure and position of its trailing vortex is studied. Spanwise load distributions determined by vortex lattice theory show that the stronger vortex moves from the tip of the wing to the hinge of the drooped tip as the droop angle increases. Experimental results on model wings are given which present the strength and the induced velocity profiles of the rolled-up vortex as a function of tip geometry. These results confirm at least qualitatively, the analytical prediction. It is concluded that a droop angle of approximately 90° is optimum and results in a maximum induced velocity which is half of that produced by a plane wing.

Some Work on the Behaviour of Vortex Wakes at the Royal Aircraft Establishment

P. L. Bisgood, R. L. Maltby and F. W. Dee
Royal Aircraft Establishment
Bedford, England

The paper reviews the work done at the Royal Aircraft Establishment on the behaviour of vortex wakes. The results of observations on the formation of loops, the behaviour of the wakes close to the ground and on the decay of the wake from a slender wing are given in some detail.

Four series of tests have been made at the Royal Aircraft Establishment. The first[1.] studied the intensity of the wake behind a Lincoln aircraft by flying a chase aircraft along the axis of one of the vortices; the strength of the vortex was assessed by the aileron deflection required to hold the induced rolling moment. The results were consistent with Squire's theory[2.] for the decay of the vortex up to a wake age of between 2 and 3 minutes, after which time the decay was very rapid. The use of flaps caused a more rapid decay.

The second series of tests[3.] studied the structure of the vortex wakes behind a Comet and a Vulcan aircraft by flying a small instrumented aircraft through the wake in a direction at right angles to the axes of the vortices. The instrumentation allowed the velocity distribution through the vortex to be measured. The results confirmed that the general structure of the vortex corresponded with that taken by Squire and that his prediction of the rate of decay of circumferential velocity was correct if a value of about 0.0002 was taken for the eddy viscosity factor.

The formation of loops[4.] in the wake about 1½ minutes after the passage of the aircraft was first observed with the Comet.

A tentative method was suggested for predicting the time taken for the loops to form based on simple similarity considerations. This gave the following expression

$$T \doteqdot 10 \, \rho \, \frac{Vb^3}{W}$$

where the factor 10 was determined empirically from the Comet tests.

The third series of tests[4.] studied the effect of ground proximity on the motion of the wake by plotting the movement of smoke trails entrained in the wake from a Hunter aircraft flying close to the ground. It was shown that the motion of the vortices in the transverse plane was accurately predicted by theory until looping occurred. The above expression predicted the time at which the loops formed quite accurately using the same constant derived from the work on the Comet. It was also observed that looping could occur in the vertical plane in the shape of half loops standing on the ground - clearly as the result of one vortex interacting with its image.

The latest series of tests studied the decay of the vortex wake behind the HP 115 slender wing research aircraft. The structure of the wake just behind the trailing edge of a slender wing is known to be complex being compounded of the strong leading edge vortex with the rolling up of the trailing edge sheet in which the vorticity is of opposite sign. The structure of this double cored vortex is only known for a few chords downstream of the trailing edge and its subsequent development in the far field is not yet understood. Clearly it would be unreasonable to assume that Squire's theory for a simple vortex wake would apply directly to this more complicated structure and the tests were designed to discover the extent of the difference.

The results of the tests appear to show that the wake decays more rapidly than Squire's theory would predict for the equivalent conventional wing. It was found that, at about 25 chords downstream of the generating aircraft, the circumferential velocities begin to decay with $(\text{time})^{-1}$ whereas the theory predicts a $(\text{time})^{-\frac{1}{2}}$ law. It has been difficult to measure the velocities closer to the trailing edge reliably but the results suggest that the $(\text{time})^{-\frac{1}{2}}$ law applies in this region although an eddy viscosity factor of about 0.0004 appears more appropriate than the 0.0002 found with the Comet.

There is strong evidence that the change in law is not directly associated with vortex breakdown which is known to occur much closer to the trailing edge in the conditions of the test. No loops have been observed in the wake although, if conventional wing conditions applied, one might expect them to form at the same time as the change in law. On the other hand there is, as yet, no reason to believe that the wake from a slender wing will produce loops at the same time as the corresponding conventional wing. At the moment, therefore, there is no basis for extrapolating this result to the conditions in the wake of a larger aircraft although it gives some reason to expect that the conditions in the wake behind a typical supersonic transport aircraft may be less severe than those in the wake of a conventional large aircraft.

---

1. Kerr, T. H. and Dee, F. W., A flight investigation into the persistence of trailing vortices behind large aircraft. ARC CP 489 (1960).
2. Squire, H. B., The growth of a vortex in turbulent flow. ARC 16666 (1954).
3. Fose, R. and Dee, F. W., Aircraft vortex wakes, and their effects on aircraft. ARC CP 795 (1963).
4. Dee, F. W. and Nicholas, O. P., Flight measurements of wingtip vortex motion near the ground. ARC CP 1065 (1969).

Span Loading and Formation of Wake

Peter F. Jordan
RIAS, Martin Marietta Corporation
Baltimore, Maryland 21227

In the exact formulation of the problem of the circular wing (Kinner 1937), it is already implied that the usual simplifying assumption of a spanwise elliptic lift distribution is not strictly correct even for planar wings of elliptic planform. An accurate solution for a finite aspect ratio wing allows one to (a) measure the performance of applied ("collocation") methods of lifting surface analysis, and (b) gain better insight into the initial formation of the wake. Therefore, the Kinner formulation is evaluated.

The pressure distribution over the planar circular wing, built up from elementary solutions, is subject to the Kutta condition and the downwash condition. The Kutta condition alone already determines the nature of the pressure singularity at the wing tips. The pressure function (obtained by factoring out the half-order singularities at the wing edges) is finite and regular along the leading edge; it jumps to the trailing edge value, zero, at the tips. (This jump represents the slender wing distribution.) Along the axis, it goes to zero as $\sqrt{\delta}\log\delta$. The local lift coefficient C_ℓ, rather than being constant, contains the same function $\sqrt{\delta}\log\delta$ and therefore has also an infinite slope at the tip, but it has a finite tip value.

The exact theory also yields solutions for spanwise wavy distributions of wing twist. The relative magnitude of the C_ℓ-waves decreases drastically as the wave length decreases; in the pressure distribution, waviness occurs at the leading edge but is completely smoothed out over most of the wing.

Regarding performance of collocation analyses: If spanwise integration is carefully performed, appreciable errors occur only at the tips. However, from apparent convergence, as the number of chordwise terms is increased, it does not follow that the correct result is reached. Pivot points on the wing edges allow one to incorporate locally both edge sweep angle and curvature radius; a flexible method results which requires few integration stations for adequate accuracy.

The mechanism of lifting line theory (1.1.th.) is such that the lift distribution, $\ell(y)$, tends toward being elliptic; conversely, if the downwash, $w(y)$, is calculated from $\ell(y)$ given, the resulting wake tends away from being planar. For the planar circular wing, therefore, the 1.1.th. wake of the exact $\ell(y)$ is pronouncedly non-planar; it involves an infinite upwash inside the tips. Thus, while the ideal planar elliptic wake is in (unstable) equilibrium, the actual wake does not require any disturbance to start rolling up.

The exact theory can also be used to evaluate the exact downwash distribution behind the wing, except behind the tips where convergence difficulties persist. Results are presented and are compared with the predictions of the usual assumption of a lifting line.

SESSION V

Stability and Decay of Trailing Vortices

An Assessment of Dominant Mechanisms in Vortex-Wake Decay

Paul B. MacCready, Jr.
Meteorology Research, Inc.
Altadena, California 91001

A basic aim in vortex-wake studies is to come up with equations which can predict the transport and decay of the organized vortex system - and can cover various aircraft types, flight modes, and meteorological conditions. There are various significant factors and mechanisms involved in the decay process, and they tend to be interrelated in a complex manner which makes it difficult to treat them separately. It is the intent of this paper to present descriptions of likely decay mechanisms, to pose questions which need to be answered to permit selection of the most realistic total picture, and to suggest means of obtaining these answers.

The significant factors in the decay outside of the ground effect include the circulation and core dimensions of the vortices, the turbulence in the wake and in the environment, and the thermal stability of the environment. The environmental factors are sometimes dominant; the vortex wakes from an airplane operating in two different meteorological regimes can differ by an order of magnitude in decay and by an order of magnitude in descent distance. Thus any theory of vortex-wake decay in the real atmosphere must consider the meteorological factors, and existing field observations on decay must be interpreted with consideration of these factors.

There are two distinct mechanisms advanced for vortex-wake decay -- the slowing down of the vortices by mixing action of eddy viscosity, and the interaction of the vortices with each other, which disorganizes the

organized vortex flow field. Presumably both mechanisms operate in any given case, but one or the other may be dominant. The slowing down by eddy viscosity is conceptually simple. The big unknown is the value (or values) to use to the eddy viscosity coefficient in a given case; empirically derived values are hard to relate to aircraft characteristics or to the environmental turbulence.

Studies of the decay of vortex pairs marked with smoke or contrails have shown that the vortex interaction mechanism commonly operates by the development of perturbations in the vortex lines on a scale an order of magnitude greater than the vortex separation distance. Existing theory seems to be useful in predicting the wavelength and shape of the breakdown, but the theory is inadequate for predicting the time of breakdown. Factors involved in initiating breakdown may include atmospheric turbulence, wake turbulence, periodic lift variations, Benard cell-type structure arising from buoyancy, and core characteristics (especially size and axial flow).

Atmospheric stability causes relative buoyancy of the wake, with subsequent effects on the vertical transport of the vortices and on their horizontal separation. The effects depend intimately upon the mixing between the wake and the environment, and so the environmental turbulence and the wake turbulence both play a role in the mechanism.

Operational rules for terminal operations of aircraft in strong turbulence should be rather easy to establish, even with the present limited stage of understanding. However, greatly improved understanding is required for predicting the worst (slowest decay) cases. Present reasoning suggests these will occur during the climbout of heavy aircraft, flying slowly in "clean" configuration, in marine air conditions where zero turbulence and near-neutral stability may often coexist.

Theoretical and Experimental Study of the Stability of a Vortex Pair

S. E. Widnall

D. Bliss

and

A. Zalay

Massachusetts Institute of Technology
Cambridge, Massachusetts 02138

The linear stability of the trailing vortex system from an aircraft is discussed. An inviscid flow model is developed for the perturbation of the rotational vortex core. A general solution is found for the self-induced velocity of a perturbed vortex core of arbitrary vorticity distribution. The amplification rate of the vortex pair instability is given for several models of the vorticity distributions in a vortex core. The model is extended to include the effects of axial velocities in the vortex core on the self-induced motion of the vortex filament. The presence of axial velocity is shown to decrease the amplification rate of the early stage (linear portion) of the vortex pair instability.

Experimental results for the distortion, break-up, and eventual decay of a vortex pair are presented.

Structure of a Line Vortex in an Imposed Strain

D. W. Moore
Imperial College, London

P. G. Saffman
California Institute of Technology, Pasadena, California 91109

The velocity of a vortex line depends on its structure, i.e., the shape of the cross-section and the detailed vorticity distribution. As a first step towards an understanding of how the structure depends on the motion and the construction of a valid approximation for the motion of vortex lines in general flow fields, we consider the structure of straight line vortices in a uniform, two-dimensional straining field. Two cases are considered in detail, irrotation strain and simple shear. In the first case, it is shown that steady exact solutions of the inviscid equations exist, in which the boundary of the vortex is an ellipse with principal axes at 45° to the principal axes of strain. There are two possible axis ratios provided $e/\omega_o < 0.15$, where e is the maximum rate of extension and ω_o is the vorticity in the core. The stability of the shapes is considered, and it is shown that the more elongated shape is unstable, while the less elongated one is stable to two-dimensional deformations. There are no steady solutions of elliptical form if $e/\omega_o > 0.15$, and it is believed from some numerical work that in this case the strain field will cause the vortex to break up. For simple shear, there is one steady shape of elliptical form if the shear rotation

and vorticity are in the same sense and e'/ω_o, where e' is the rate of shear. The major axis is parallel to the streamlines and the shape is stable to two-dimensional deformations. For shear rotation and vorticity in opposite senses, there are two steady elliptical shapes if $e'/\omega_o < 0.21$, with major axes perpendicular to the streamlines. The more elongated form is unstable, and the less elongated one is stable. Disturbances of three-dimensional form are also considered in the limit of extremely large axial wavelength.

A New Look at the Dynamics of Vortices with Finite Cores

P. C. Parks
University of Warwick
Coventry, England

and

NASA - Langley Research Center
Hampton, Virginia 23365

The stability theory for wave-like disturbances in a pair of trailing line vortices developed by S. C. Crow has been modified to take account of finite core radii and appropriate distributions of vorticity within these cores. The difficulties encountered by Crow in calculating the self induction effects of each vortex are avoided and, for a uniform distribution of vorticity within the cores, the self induction function is expressible in terms of modified Bessel functions of the second kind. The essential features of Crow's theory are, however, confirmed with small numerical changes - for example, the most unstable long waves have a wavelength of 7.2b, where b is the separation distance of the two vortices, compared with Crow's result of 8.4b.

The effect of longitudinal flow within the cores may be considered by wrapping the core in a sheet of vortex rings, but this affects only the imaginary parts of the eigenvalues encountered in the problem and so the stability diagrams, which depend on the real parts, are unaltered.

The theory, which assumes the vortices extend from infinity to infinity, cannot be used to calculate the growth of perturbations

deliberately introduced at the wing of the aircraft, but a modified discretised theory amenable to digital computation has been developed.

Decay of an Isolated Turbulent Vortex*

Coleman duP. Donaldson
Aeronautical Research Associates of Princeton, Inc.
Princeton, New Jersey 08540

A review is given of the work being carried out at A.R.A.P. under Air Force support to develop a scheme for computing the behavior of an axially symmetric turbulent vortex flow in which both the axial and radial components of velocity, as well as the azimuthal velocity, are taken into account. The method used to obtain the basic equations for such a turbulent flow is the method of invariant modeling that has been under development at A.R.A.P. for the past few years.

In the first part of the paper, the general equations for an isolated line vortex, as derived by invariant modeling, are presented. The basic nature of these equations is then examined in relation to similar equations for parallel shear flows. Certain general features of the types of motion that can exist for such axially symmetric vortex flows are discussed.

As an illustration of the method, calculations that have already been computed for the time-dependent decay of an infinite vortex for which axially velocity is zero are presented.

---

*This research is sponsored by the Air Force Office of Scientific Research, Office of Aerospace Research, under Contract F44620-69-C-0089.

Finally, an experimental apparatus that has been recently completed at A.R.A.P., which will permit a detailed comparison of these calculations with experimental measurements of the decay of an isolated vortex, is presented.

Decay of a Vortex Pair Behind an Aircraft

Jack N. Nielsen and Richard G. Schwind
Nielsen Engineering & Research, Inc.
Mountain View, California 94040

A theory is presented for calculating the characteristics of a turbulent vortex pair behind an aircraft including its rate of decay. The method is developed for the case of no atmospheric disturbances. It yields equilibrium conditions needed as inputs into any small disturbance stability analysis.

It is envisioned that three phases occur in the development and decay of the trailing vortex system. First the wake from the wing (other circulation sources are neglected) rolls up from a sheet into a spiral a short distance behind the aircraft. Thereafter each vortex of the pair acts essentially as an isolated turbulent vortex, and increases in size as it moves downstream. At some point the individual vortices have enlarged sufficiently that vorticity of opposite signs diffuses to the plane of symmetry and annihilation of the trailing vortices gradually takes place. A separate analysis covers each of these three phases. The first phase is handled by tracking the movement of discrete vortices as done by Westwater.

The second phase has been analyzed by a method similar to boundary-layer integral methods. The vortex is considered to have three regions in its radial circulation profile, as suggested by Hoffman and Joubert. The first is the "eye of the vortex" in solid body rotation, the second is the logarithmic law region, and the third is the outer or defect

region. These regions are similar to the laminar sublayer, law-of-the-wall region, and defect region in turbulent boundary layers. Using the experimental results of Hoffman and Joubert as a basis, empirical expressions are developed for the circulation profile in each region. These expressions are put into integral vortex relations to obtain differential equations for the variation of the vortex characteristics with streamwise distance. Solution of these equations yields the vortex outer radius, r_o, and the point of maximum tangential velocity, r_1, as functions of streamwise distance.

The third phase starts when r_o is sufficiently large that the vortices interact. Vorticity annihilation then occurs, and the circulation of each vortex decreases with time. Calculations based on two-dimensional viscous-flow theory are made to determine the rate of decrease of circulation.

Based on the foregoing theory, a set of illustrative calculations are carried out for a heavy transport at sea level to show the characteristics of the overall solution. Several important parameters, such as the eddy viscosity and the initial values of r_o and r_1, are varied to show their effects on the overall solution.

The paper will conclude with the description of a proposed ground facility for the creation of long trailing vortices.

SESSION VI

Aircraft Response to Wake Turbulence

Results of The Boeing Company Wake Turbulence Test Program

P. M. Condit and P. W. Tracy
Boeing Commercial Airplane Group
Seattle, Washington 98124

The potential hazards of wake turbulence to air traffic have been recognized for many years. The development of large jet transport aircraft led to concern that the turbulent wakes generated by these aircraft would create a significantly increased hazard. The Boeing Company initiated a study of large jet airplane wake turbulence in mid 1969. It was found that analytical predictions of trailing vortex strength relied heavily upon the extrapolation of data gathered on relatively small airplanes. The Boeing flight test program was undertaken to evaluate the behavior of trailing vortices and to obtain a direct comparison between the turbulent wakes of the 747 and a 707-320C. The 747 and 707 were equipped with smoke generating equipment to mark their trailing vortices. A fully instrumented Boeing 737-100 was used as the primary wake probing aircraft. Additional probes were made with the Boeing owned F-86 and NASA's CV-990. These encounters indicated little or no difference, in terms of dynamic response, between the wakes of the 747 and 707. The 737 was also flown in the turbulent wake of the 747 on approach to landing in order to assess the effects of wake turbulence during approach and in ground effect. It was observed that when the 747 was in ground effect its wake did not form into concentrated vortices and the turbulence was relatively weak.

Aircraft Response to Turbulence Including Wakes

John C. Houbolt
Aeronautical Research Associates of Princeton, Inc.
Princeton, New Jersey 08540

The nature of atmospheric turbulence and the means for establishing aircraft response is reviewed, both from discrete-gust and spectral interpretations. Application is then made to the situation of wake turbulence encounter to show the nature and magnitude of the loads that results. Various specific cases are treated, with encounters perpendicular to and parallel to the wake, to bring out the main parameters that are significant. General relations are also developed to show how the wake "gust" forces on the encountering airplane are related to the lift on the aircraft generating the wake.

Airloads and Moments on an Aircraft Flying Over A Pair of Inclined Trailing Vortices*

W. P. Jones and B. M. Rao
Texas A&M University
College Station, Texas 77843

When an aircraft flies across the wake of a preceding one, it is subjected to changing airloads and moments induced by the trailing vortices of the first aircraft. The purpose of this paper is to investigate the magnitude and characteristics of the time dependent aerodynamic forces so produced. Both aircraft are assumed to be in horizontal flight but the direction of flight of the second aircraft is assumed to be inclined at a small angle to the trailing vortices of the first aircraft. The airloads then will change relatively slowly with time and may be estimated with reasonable accuracy by quasi-steady aerodynamic theory without taking Wagner growth of lift effects into account. In the present study, the pilot of the second aircraft is assumed to have sufficient control power to maintain his aircraft in level flight. However, in practice, this condition is likely to be violated when the aircraft is close to one of the trailing vortices of the leading aircraft, particularly when the latter happens to be a large transport plane. In such circumstances the following aircraft could stall and would, in any case, be subjected to big changes of rolling moment as indicated by the results presented. In the development of the theory it is assumed that the trailing vortices are a chord length or more below the following aircraft and that the vorticity distribution over its wings will have negligible effect on the trailing

vortices themselves. The pair of vortices will give rise to an upwash distribution over the aircraft's wings which must be balanced by an equal and opposite velocity distribution induced by the vorticity distribution over the wing. The problem then is one of finding the appropriate vorticity distribution at each stage of the aircraft's flight over the trailing vortices. This can be done approximately by using a modified lifting line theory or, more accurately, by lifting surface theory. To illustrate the methods of analysis employed, calculations were done for an aircraft with rectangular wings, but only the airloads on the wings were determined. Values of the lift, rolling moment and pitching moment coefficients, corresponding to vortex inclinations of 10°, 20°, and 30°, were obtained for a rectangular wing of aspect ratio 6 at different times during its passage over the trailing vortices.

---

*Work supported by the U. S. Army Research Office, Durham, under Project Themis Contract DAHC04-69-C-0015.

Flight Evlauation of the Wing Vortex Wake Generated by Large Jet Transports

William H. Andrews
NASA Flight Research Center
Edwards, California 93523

A flight program has been conducted to update the current level of knowledge relative to the behavior of wing wake vortices generated by existing large transport aircraft and future jumbo jet transports. The tests were conducted to evaluate the wake location, persistence, apparent intensity, and influence out of ground effect and primarily under terminal area configuration and operational conditions.

The generating aircraft used were considered to be a cross-sectional representation of the transports in service and covered a gross weight range from 165,000 to 610,000 pounds. This group of test aircraft included a Douglas DC-9, Convair 990, and Lockheed C-5A.

The wake behavior was evaluated by measuring aircraft response and controllability of a series of probe airplanes flying in the generating aircraft wake at separation ranges from 1 to 15 nautical miles. The probe airplanes included a Lockheed F-104, Cessna 210 and 310, Lear Jet 24, DC-9, and the Convair CV-990. These airplanes were instrumented to record standard handling qualities parameters; however, the primary analysis was based on the probe airplane roll response and control inputs to counteract the induced rolling moment produced by the wake of the generating airplane. The generator-to-probe airplane separation ranges were resolved from simultaneous radar tracking of the aircraft with FPS-16 radars.

Aircraft Wake Turbulence Controllability Experiment

Robert P. Johannes
Air Force Flight Dynamics Laboratory
Wright-Patterson Air Force Base, Ohio

The two most critical areas of concern with respect to operating aircraft in the presence of other aircraft wake turbulence are the structural loads experienced and possible vehicle upset resulting from vortex encounter. The Load Alleviation and Mode Stabilization (LAMS) Advanced Development Program recently completed by the Laboratory has shown that automatic control can offer significant improvements in both areas.

This paper addresses the flight experiment which was conducted to evaluate the effectiveness of an advanced flight control system in preventing upset when a large aircraft is immersed in the wake of a leading large aircraft. The LAMS B-52 test aircraft was flown in the wake of a C-141 to obtain data on the vortex characteristics and the improved controllability provided. The results of the experiment indicate that the vortex velocities are somewhat greater than predicted by theory and that the automatic control system can significantly improve aircraft control in the presence of wake turbulence. Undesired roll attitude excursions were reduced from $\pm 10°$ to $\pm 4°$, and pilot activity in attempting to keep wings level was drastically reduced from $\pm 60°$ to $\pm 10°$ control wheel input.

It is concluded that control systems which take into account the structural characteristics of the vehicle such as the LAMS system can do much to minimize the wake turbulence problem.

SESSION VII

Control and Use of Trailing Vortices

An Estimate of the Power Required to Eliminate Trailing Vortices by Suction

J. Menkes
University of Colorado
Boulder, Colorado 80302

F. H. Abernathy
Harvard University
Cambridge, Massachusetts 02138

The fullest utilization under instrument flight rule (IFR) conditions of closely spaced parallel runways might very well depend ultimately on our ability to eliminate or at least to control the hazards of wake turbulence. The actual hazard is due to the possibility that the disturbance created over one runway will drift in an uncontrolled manner to a neighboring one.

A descending aircraft is affected by the interaction of its vortex system with the ground; if the ground effect could be modified, the vortex reaction would be affected. Such a modification is induced by suction. Suction in effect "removes" the ground and thus lets the vortices drift downward rather than horizontally. The vortex motion is thus influenced without relying on viscous dissipating mechanisms. The conceptual scheme involves placing one or more ditches which house the suction blowers between the runways.

The computer simulation of this scheme indicated the following main points.

1) The most adverse condition is presented by a weak vortex and winds of the order of 6 mi/hr or more.

2) The most favorable situation arises in the absence of wind and when the vortex is very strong, e.g., due to the takeoff of a Boeing 747. Under those circumstances, the vortex drifts almost solely under its own induced motion into the ditch.

3) In most other cases one can expect a suction velocity of 10 ft/s or less to clear the runway of any vortex located at 100 feet above ground in 70 seconds or less.

4) The horsepower required is governed by the exit port rather than the suction inlet.

5) A conservative estimate is 2000 hp for a ditch with a surface area of 1×10^5 ft^2, two exit ports of about one-third this size, and a suction velocity of 10 ft/s.

6) The suction velocity over the runways is approximately 1 ft/s.

7) Increases in the horsepower do not substantially decrease the time required to suck down the vortex.

8) A secondary benefit derives from the possibility of using suction to clear the field of snow and ground fog.

Fog Formation and Its Dispersal by Trailing Vortices

P. O. Baronti and S. Elzweig
Advanced Technology Laboratories, Inc.
Jericho, New York 11753

Fog, once little more than a nuisance, has now become a serious hazard to modern high speed travel. The work contained herein consists of:

(1) the physics of fog, and,

(2) fog dissipation utilizing the vortex downwash of a hovering helicopter.

The existence of fogs apparently defies the intuitive notion that, in the absence of an upward velocity, the water droplets should fall because of gravity, and hence the fog should disappear. A novel approach is presented here to explain why fog can be maintained for extended periods of time, even in the absence of vertical velocities. It is shown that particle diffusion, either brownian and/or turbulent is insufficient to maintain the fog. The model presented here considers the fog as a dynamical system whereby droplet depletion through fall is balanced by a continuous process of evaporation and condensation. The controlling parameters of the process are the heat transfer from the ground and the level of turbulence. Numerical examples are presented.

Recent experiments suggest that a promising method of fog removal can be achieved by flying helicopters above the fog surface in order to utilize the vortex downwash to force air above to mix with the moisture

laden air below. If the air above the fog is sufficiently dry or warm, the decreased humidity of the resulting mixture permits evaporation of the fog droplets. Notable success in clearing holes of lateral extent many times the size of the helicopter rotor has been reported.

A plausible mechanism, in light of the aforementioned experiments, for the creation of holes through a fog layer by a helicopter wake is established. The proposed mechanism is employed to theoretically analyze, in the presence of a ground, the fog clearing process. The analysis is accomplished by dividing the flow field into a free jet region and an impingement region. Results for a helicopter hovering at several heights above a fog layer are presented.

NOTES

NOTES